CONTRIBUTION TO IMPROVE PILLAR ANALYSIS IN ABANDONED ROOM AND PILLAR SATL MINES

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ABSTRACT: The long-term behavior of old abandoned salt mine openings is an important question from a safety assessment viewpoint. For room and pillar mines, a simple is proposed method to improve the accuracy of the classical pillar stability analysis methods. The first part of this method deals with pillar behavior by taking into account the mechanical interactions "pillar-roof" and "pillar-floor". This is achieved by means of finite element computations. These computations allow to perform a substantial correction of the classical pillar's failure criterion. The comparison of results of various finite element analyses with those of real cases validated this method.

KEYWORDS : Salt mines, room and pillars, stability, finite elements, creep

RESUME : Le comportement à long terme d'anciennes exploitations de sel est une question primordiale du point de vue de la sécurité. Nous proposons une méthode simple pour l'analyse des mines de sel exploitées par la méthode des chambres et piliers abandonnés. La méthode prend en compte la contribution mécanique du sommet et de la base des. Au vu du caractère non homogène et non-linéaire du problème aux limites, l'objectif est atteint en ayant recours à la modélisation numérique. Les abaques issus de cette méthode permettent une correction significative de la sollicitation évaluée par la méthode de l'aire tributaire. La méthode proposée est validée par la comparaison de résultats issus de cette nouvelle méthode avec des mesures effectuées in-situ.

MOTS-CLEFS : Mines de sel, chambres et piliers, stabilité, éléments finis, fluage

1. Introduction

Several salt deposits in France were exploited using different methods (solution-mining, room and pillar mines, etc.). The depth of a salt deposit can be different from one site to another (several hundred meters). Many salt mines are more than one century old. After several decades of exploitation, many of salt's mines in France have been abandoned, leaving significant residual voids underground. The existence of such voids, with various sizes, raises the question of the long-term stability of those mines as well as their potential impact on safety of population and structures located on surface. This paper deals only with abandoned room and pillar salt mines.

Within the framework of geomechanical stability analysis of salt mines, "time" is a significant parameter since rock salt is characterised by a well-known strongly time-dependent behavior. The classical method used in order to assess pillars stability, in room and pillar mines, is usually based upon the *tributary area method*. From a safety viewpoint, this method is well appropriated when it is applied within a design framework. Nevertheless, its formulation is not accurate enough for checking or establishing the current stability of old abandoned room and pillar mines.
In fact, the formulation of this method is based on two major assumptions. The first one considers the overburden, whatever its mechanical features, as a simple dead load. The weight of overburden layers is so fully supported by the pillars. The second assumption, the one analysed in this paper,

deals with pillar-roof and pillar-floor interactions. In fact, the *tributary area method* considers perfectly smooth contacts, with no shear stress at the pillar's ends (contact surfaces).

In this paper the authors focus on the second assumption. The shear stresses acting at the ends of the pillar are in general not negligible. They can in fact increase significantly the strength or the stability of the pillar by reducing deviatoric stresses, regarding plasticity framework, and decrease the creep strain, in a viscoplastic framework. The value of deviatoric stress strongly depends on the geometry of the pillar, more exactly, on the slenderness ratio (λ). This one is defined as the ratio of the height H of the pillar over its width L : $\lambda = H / L$.

One could easily bypass these two major assumptions by performing a numerical computation of such mechanical problems (finite element computation for instance). Unfortunately, the geometrical sizes of a mine and its mechanical history are such, as it becomes almost impossible to perform an accurate numerical modelling of the overall problem. In order to improve, the *tributary area method*, we propose a simple method to correct the classical method through factors identified numerically on a single pillar. These correcting factors take into account the interaction between pillar and roof and pillar and floor. This method is developed in the case of plasticity and also in the case of viscoplasticity by taking creep into account.

When taking into account the shear strength acting at pillar boundaries, it is observed that the reduction factors are non-linear functions of slenderness ratio. Several numerical computations have been performed for different slenderness ratio, material parameters and loading cases. The validity of this method was checked successfully by comparing results of various finite element analyses with data related to real cases.

2. Current method for assessing salt mine pillar stability

This section is devoted to a brief description of the classical *tributary area method* and its main assumptions.

We suppose, for sake of simplicity, that the strata layers and the mine are horizontal. Under this assumption, the *tributary area method* states that the stress acting in the pillar is:

- Homogeneous $\underline{\underline{\sigma}}(x,y,z) = \underline{\underline{\sigma}}, \forall (x,y,z) \in \Omega_{pillar} \subset \mathbf{R}^3$,

- The second order Cauchy stress tensor is completely defined by only a single component:

$$\boldsymbol{\sigma} = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{xy} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{xz} & \sigma_{yz} & \sigma_{zz} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \sigma_z \end{pmatrix}$$

The value of the stress component σ_z depends on the thickness of the overburden layers and the extraction ratio (τ) which is classically defined as follows:

$$\tau = 1 - \frac{(Lp)^2}{(Lp+w)^2} \tag{1}$$

where Lp and w are respectively the widths of the pillar and of the room. The overburden thickness

H_r is a purely weighing stratum (dead load). Under these considerations, the averaged vertical stress σ_z is then equal to:

$$\sigma_z = \sigma_{TAM} = \frac{\gamma H_r}{1-\tau}, \tag{2}$$

Where γ is the specific weight of the overburden. Let us call σ_{TAM} this vertical stress defined by the Tributary Area Method. In stability analysis framework, currently, the averaged stress σ_{TAM} is compared with the uniaxial compression strength Rc, which is expressed in the framework of a Mohr-Coulomb failure criterion as follows:

$$Rc = \frac{2C\cos(\phi)}{1-\sin(\phi)} \tag{3}$$

C is the cohesion and ϕ the angle of internal friction of the pillar material.

3. Factors of correction of the classical method for assessing stability of salt mines pillars

In the short description of the Tributary Area Method below, one can note that neither the contribution of the roof nor the pillar form are taken into account in the expression. The mechanical contribution of the overburden is very difficult to measure. It depends on several geometrical and mechanical parameters such as, geometry of the exploitation, the geomechanical characteristics of the overburden, the history of the exploitation (phases of extraction) etc. The ends of pillars are assumed with no shear stress and no kimenatical constrains (acting or prescribed).

In order to improve, the tributary area method, we propose to apply a multiplying correction factor to the averaged stress σ_{TAM}, as follows:

$$\bar{\sigma} = C_{RE} \times C_P \times \sigma_{TAM} \tag{4}$$

In this expression C_{RE} is a factor, which takes into account the mechanical contribution of the overburden. The value of the coefficient $C_P \leq 1$ expresses the mechanical contribution of the pillar shear acting on its ends, leading to a confining pressure (in average). The first factor C_{RE} deals with the intensity of the loading applied to the pillar. It can be considered as a *loading factor*. The second factor C_P is linked to the *structural* pillar strength. It can be considered as a *strength factor*.

The expression (4) is more explicit when written as follows:

$$\bar{\sigma} = C_P \times \left(C_{RE} \times \sigma_{TAM}\right) \tag{5}$$

Since C_P and C_{RE} are known, in order to assess stability of the pillar or to perform a creep analysis of the pillar, σ_{TAM} will be substituted by $\bar{\sigma}$.

We suppose in the following development that $C_{RE} = 1$.
The factor C_P is determined numerically using finite element computations. This is principally due to the difficulty to express analytically the solution of such non homogeneous IBV (initial non-linear boundary value) problems.

4. Definition and values of C_P : assumptions and methods

The figure below shows a schematic representation of a typical room and pillars mining: pillar, rooms, floor, roof and overburden.

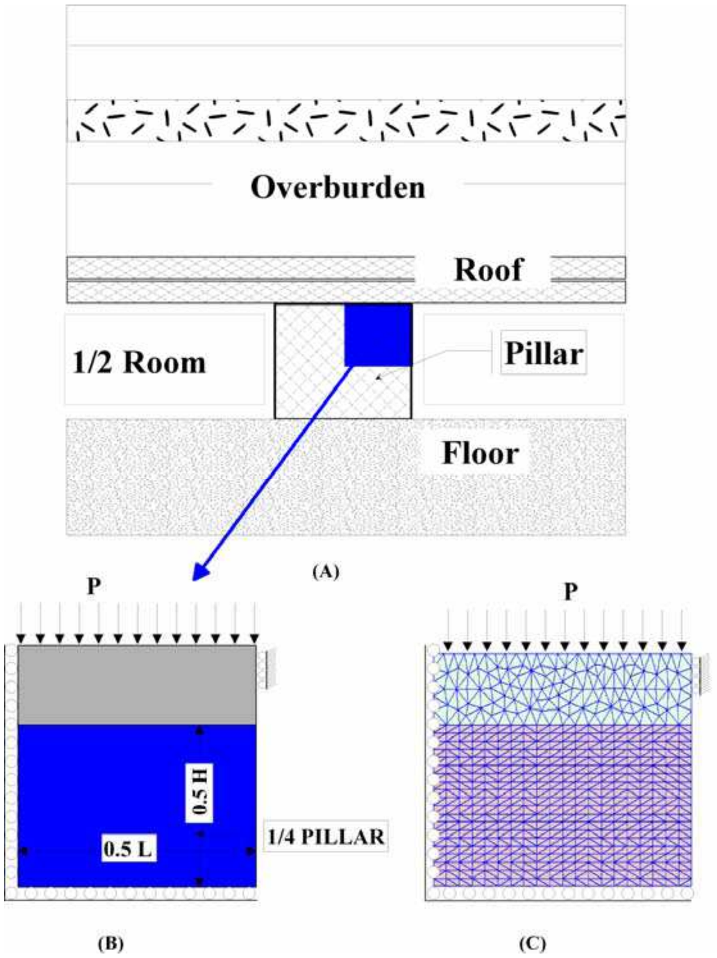

Figure 1. Schematic plan of the pillar and the overburden (A), geometric model (B), finite elements model (C).

Finite element analysis is performed in axisymmetric condition. The width of the pillar corresponds then to the diameter of the model. We assume also the existence of a symmetric plane perpendicular to the pillar. Thus only ¼ of the pillar is modelled. An elastic domain with variable Young modulus (Figure 1C) replaces the overburden. A *dead load P* is applied on the top. The boundary conditions are also shown in Figure 1C. Since basically the pillar behaviour view is considered, roof and floor have been supposed to be stable.

4.1. Elastoplatic analysis

In an elastoplastic analysis framework, the load *P* is increased smoothly until the failure of the pillar is reached. The pillar failure criterion is then defined by the lost of convergence of the iterative process used in order to solve the non-linear problem. $\bar{P}$ is called the load leading to failure of the pillar. It is to be noticed that, in this present approach, no bifurcation analysis as defined by Rice (1974) or Hill (1958) was performed. In plasticity, a Mohr-Coulomb model is used to describe the local failure criterion.

When the pillar failure is reached, C_P is defined as follows:

$$C_P(\phi, C, E, \nu, \lambda) = \frac{Rc}{\overline{P}} \text{ with } \lambda = \frac{H}{L} \tag{6}$$

In elastoplastic analysis, the factor $C_P(\phi,C,E,\nu,\lambda)$ should depend on friction angle ϕ, cohesion C, Young modulus E, Poisson's ratio ν and slenderness ration λ of the pillar. Many finite element computations have been performed, and the parametric analysis performed through these computations concluded that C_P is mainly function of λ and ϕ. In other words, for a pillar with fixed ends (no slide at the interfaces), $C_P \equiv C_P(\phi, \lambda)$.

4.2. Elasto-vicoplastic or creep analysis

This study deals with salt mine pillars. Among different constitutive models of salt (Cristescu & Hunsche, 1991,1998), we choose the Lemaitre power-law model (Lemaitre,1988) expressed in rate form as follows:

$$\frac{\partial \boldsymbol{\varepsilon}^{vp}}{\partial t} = A e^{\left(\frac{-B}{T}\right)} \left(\frac{\sigma_{eq}}{\sigma_0}\right)^{n} \left(\varepsilon_{eq}^{vp}\right)^{m} \frac{\partial \sigma_{eq}}{\partial \boldsymbol{\sigma}} \tag{7}$$

Where $\boldsymbol{\varepsilon}^{vp}$ is the second order vicosplastic strain tensor, $\boldsymbol{\sigma}$ the Cauchy stress tensor , σ_{eq} the Von Mises equivalent stress ($\sigma_{eq} = \sqrt{\frac{3}{2}\boldsymbol{s}:\boldsymbol{s}}$) where $\boldsymbol{s}$ is the deviatoric stress tensor $\left(\boldsymbol{s} = \boldsymbol{\sigma} - \frac{tr(\boldsymbol{\sigma})}{3}\mathbf{I}\right)$. The hardening parameter is the equivalent viscoplastic strain defined as $\varepsilon_{eq}^{vp}\left(\varepsilon_{eq}^{vp} = \sqrt{\frac{2}{3}\boldsymbol{\varepsilon}^{vp}:\boldsymbol{\varepsilon}^{vp}}\right)$. σ_0 is the reference stress value (1 MPa), and, finally, T is the temperature in Kelvin. In the finite code VIPLEF, used in our study and in the following development, the model will be rewritten as follows (1-D case) :

$$\varepsilon^{vp} = 10^{-6}\left(\frac{\sigma_{eq}}{K}\right)^{\beta} t^{\alpha}, \quad \left[\frac{m}{m}\right] \tag{8}$$

The authors emphasize on the fact that choosing the over-mentioned constutive model, one can easily get the well-known Norton law for wich $\alpha = 1$ or m=0. This is why, in this study we preferred to use the general expression rather than the specific case of Norton law which is very common for salt.

In presence of viscosity, the mechanical problem becomes obviously a time-dependent or rate depend problem. The corrected value of the average vertical stress σ_{TAM} leads to the following scalar equation:

$$\varepsilon = \frac{CV}{H} = \varepsilon = \varepsilon^{e} + \varepsilon^{vp} = \frac{C_{RE}C_P\sigma_{AT}}{E} + \left(\frac{C_{RE}C_P\sigma_{AT}}{K}\right)^{\beta} t^{\alpha}$$

(9)

Where CV is the floor-roof closure, and ε the averaged axial or vertical strain.

The expression of C_P does also depend on several parameters such $C_P = f(E,\nu,\lambda,\alpha,\beta,K,t)$. Many finite element computations have also been performed in this case. The parametric analysis performed through these computations concluded that C_P is only function of λ and t, in other words $C_P = C_P(\lambda, t)$, at short term and C_P is only function of λ at long term. In fact, C_P quickly reaches an asymptotic value. The value of $C_P(\lambda, t)$, for a given pillar geometry defined by λ and at a given time t_n, is the solution of the following non-linear scalar equation:

$$\frac{C_P(t_n,\lambda)\sigma_{AT}}{E} + \left(C_P(t_n,\lambda)\right)^{\beta}\left(\frac{\sigma_{AT}}{K}\right)^{\beta} t_n^{\alpha} - \bar{\varepsilon}(t_n) = 0 \tag{10}$$

5. Factors of correction

The figures below shows the finite element computation of C_P both, in the cases of a creep and plasticity analyses.

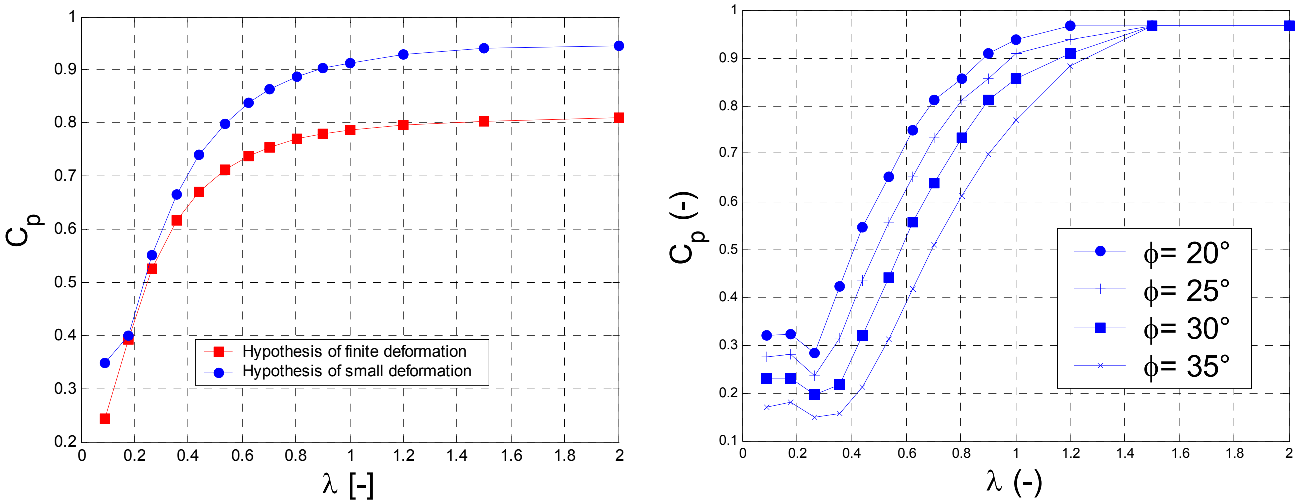

Figure 2. Factor of correction C_P for creep analysis (left) and plastic analysis (right).

One can notice the strong influence of the slenderness ratio λ on C_P and also its dependence on the friction angle ϕ. This last contribution is naturally linked to the fact that the shear stress acting on the boundaries of the pillar generates a non homogeneous confining pressure inside the pillar, and thus it will move out the average stress state far from the Mohr-Coulomb failure plane.

6. Example of application in case of salt pillars creep

This example deals with a real case of a salt mine exploited by room and pillars method. This mine is located in the East of France. The pillar height is 4.5 meters and the extraction ratio τ is equal to 75%. A part of the mine of about 110 years old: this is located at about 135 m deep. In this area the pillars are of square section of 10 by 10 meters. A thick salt layer has been left in the roof. The second part of the mine of about 70 years old is located at about 143 m of depth. In this area the pillars are of square section of 15 by 15 meters. A thick salt layer has been also left in the roof. Two analyses were performed in order to describe evolution of the axial (vertical) *averaged* pillar strain (deformation).

The first one used finite element analysis (Fig. 3)

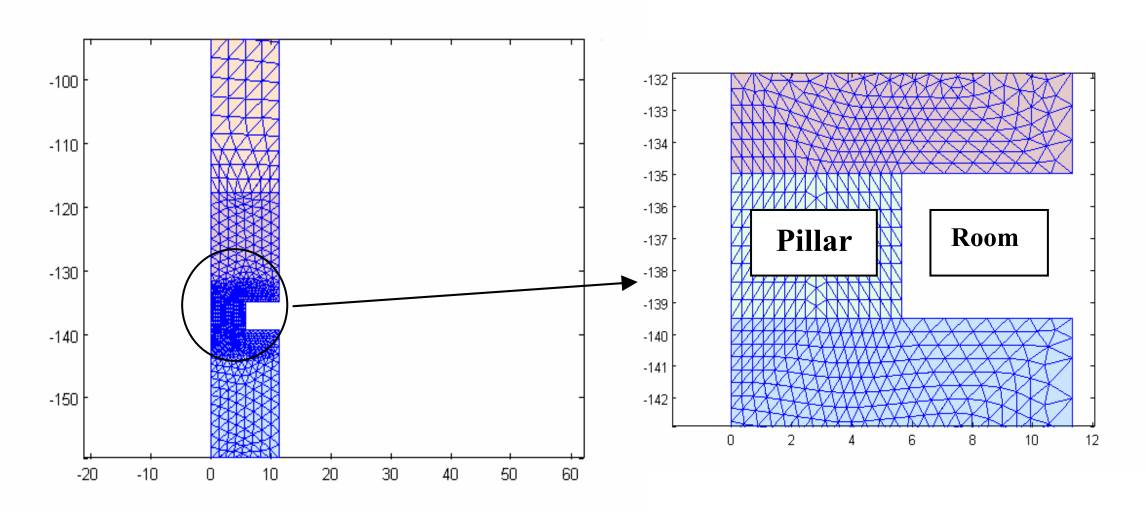

Figure 3. Finite element mesh of the mine (pillar-roof-room, left-hand) and detail of the pillar mesh (right-hand).

The second computation used the corrected method described below. The comparsion of the résults are shown in Figures 4 and 5.

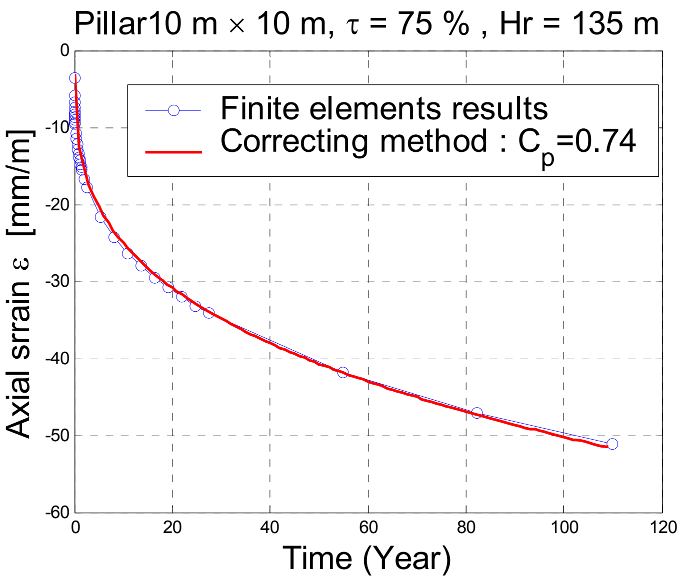

Figure 4. Comparison of the result obtained with finite element computation and the proposed correcting method.

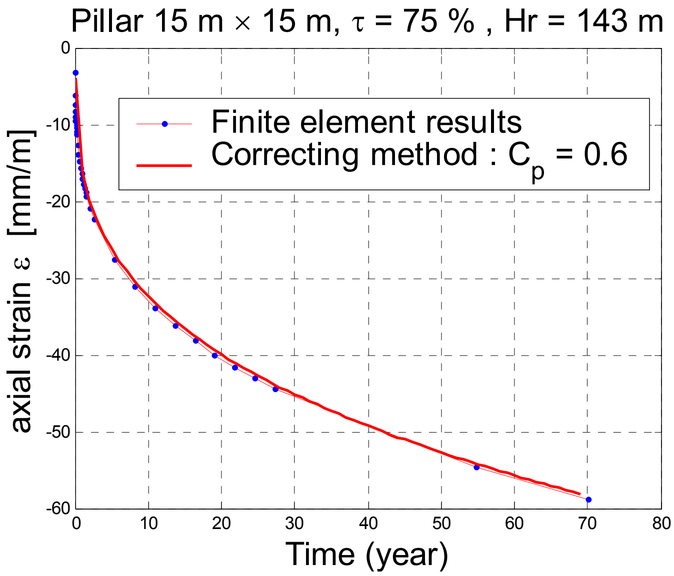

Figure 5. Comparison of the result obtained with finite element computation and the proposed correcting method.

One can realise that, through the simple analytical method proposed above, the results are almost the same as those obtained using a complex finite element modelling. The current strain rates, measured in situ, are the following: 0.148 mm/m/year for the first case and 0.214 mm/m/year for the second case. With the factor of correction and using tributary area method we obtain: 0.142 mm/m/year for the first case and 0.252 mm/m/year in the second one. Indeed the suggested method fits quite well with field data.

7. Conclusion

The results presented above show up clearly that for the purpose of long term analysis of room an pillar salt mines, both mechanical stability and time-dependent displacement of the pillars can easily be evaluated using the suggested method. This method has been elaborated by a series of finite element computations in elastoplasticity (pillar stability) and in viscoplasticity (pillar creep). The results allowed to express correcting factors than can be used together with the classical tributary area method.

The suggested method has been validated by data from real salt mines. It can be applied successfully to room and pillar salt mines without any complicated numerical computations (F.E. method). Nevertheless, the results are very accurate and the method is very easy to use.

In this study, the overburden is assumed as a dead load applied to the pillars. The mechanical contribution of an overburden containing stiff layers requires further studies leading to a complementary correcting factor.

8. References

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